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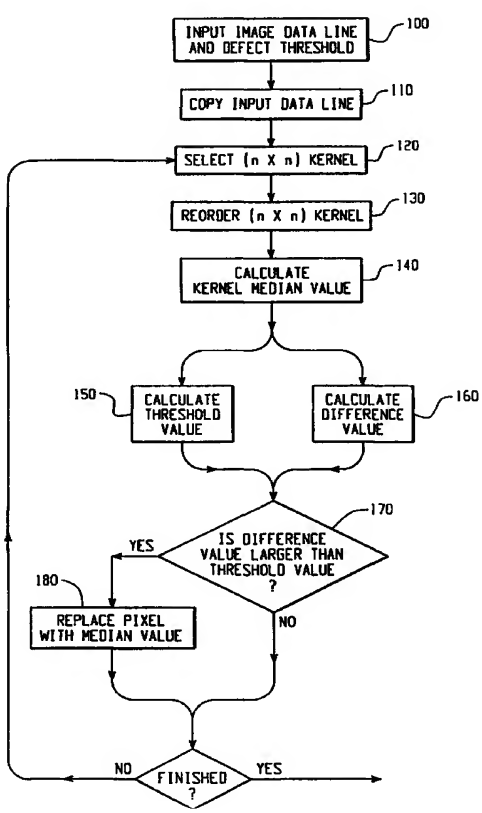

(57) Abstract: An adaptive median filter (32) provides dynamic detection and correction of digital image defects which are caused by defective or malfunctioning elements of a radiation detector array (20). The adaptive median filter receives (100) lines of pixel values of a digital image that may have defects and a user-defined defect threshold. The lines of pixel values are scanned on a pixel-by-pixel bases using a kernel of nxn pixels, where the kernel contains the candidate pixel being examined (120). Each kernel is numerically reordered (130) and a median value is calculated (140). A defect threshold value is calculated by multiplying the user-defined defect threshold criteria (44) and the candidate pixel value (150). A reference value is calculated by subtracting the candidate pixel value and the median value (160). The reference value is compared to the defect threshold value (170). The candidate pixel value is replaced by the median value (180) if it differs from the median value by more than the predefined defect threshold, e.g., 20 %. The adaptive median filter is particularly effective in detecting and correcting double line and double column defects in digital images. In addition, the filter minimizes image blurring and maintains image resolution by filtering only defective pixels.

WO 02/05213 A2

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METHOD AND APPARATUS FOR DIGITAL IMAGE DEFECT CORRECTION AND NOISE FILTERING

Background of the Invention

The present invention relates to the art of digital image defect correction. It finds particular application in conjunction with diagnostic imaging in fluorographic and fluoroscopic systems having flat panel radiation detectors and will be described with particular reference thereto. It is to be appreciated, however, that the invention will also find application in conjunction with CCD imagers, solid state image pickup devices, conventional x-ray diagnostic systems, computerized tomographic scanners, and other radiation detection systems for medical and non-medical examinations.

Typically, fluoroscopy includes a plurality of image intensifiers or two-dimensional, flat panel radiation detectors which convert X-ray radiation traversing a patient examination area into electronic signals. Each radiation detector includes a radiation sensitive face, such as a scintillation crystal, which converts the received radiation into a corresponding quantity of light. Solid state diodes are often provided to convert the light emitted by the scintillation crystal into analog electrical signals indicative of the intensity of the crystal emitted light, hence the intensity of the received radiation. The analog signals are converted into corresponding digital signals which are reconstructed into digital images.

Unfortunately, many flat panel radiation detectors, especially large-area flat panel detectors, contain single pixel defects, line defects, double-line defects, and column defects which lead to the generation of defective digital image representations. Prior art techniques correct such pixel, line, and column defects with a series of processes, typically consisting of defect map correction and median filtering. In defect map correction techniques, a base defect map of each panel detector is created during the manufacture of the flat panel detector. Additional defect maps may be created during subsequent calibrations of the panel detectors. These defect

maps are used for the first order detection of permanent defects in the panels and interpolations, such as a median filter, are used to correct these permanent defects. A median filter algorithm is also applied to the entire image in order to provide secondary defect correction for random defects that do not have fixed patterns. This multi-phase defect correction process suffers from processing complexity and inefficiency.

Conventional median filter algorithms adjust all of the pixels of an image representation. In other words, each pixel of an image is replaced by the median value of the pixels in the neighborhood of the particular pixel being examined. This type of median filtering blurs images, which results in great reduction in image resolution. Further, conventional median filters cannot correct double line and double column defects. In fact, conventional median filters can introduce additional image defects by incorrectly replacing pixels adjacent to defective lines and columns with median values of neighborhood pixels.

The present invention contemplates a new and improved method for detecting and correcting digital image defects which overcomes the above-referenced problems and others.

Summary of the Invention

In accordance with one aspect of the present invention, a method for real-time detection and correction of digital image defects due to defective detector pixels includes identifying a candidate pixel value in image data, which includes a plurality of candidate pixel values and corresponding kernels of neighboring pixel values. For each candidate pixel value, a reference value is calculated from the neighboring pixel values. The method further includes comparing a relationship between the candidate pixel value and the reference value with a threshold criterion. Based on the comparison, either the candidate pixel value is replaced with a function of neighboring pixel values or the candidate pixel value is retained.

In accordance with another aspect of the present invention, an adaptive median filter for detecting and

correcting defects in a digital image representation due to defective detectors in a radiation detector array includes a memory which stores each candidate pixel value and neighboring pixel values. A processor calculates a reference value from the neighboring pixel values and compares a relationship between the candidate pixel value and the reference value with a threshold criterion. Based on the comparison, either the candidate pixel value is replaced with a function of the neighboring pixel values or the candidate pixel value is retained.

One advantage of the present invention is that it simplifies the detection and correction of defects in images acquired using flat panel radiation detectors.

Another advantage of the present invention is that it corrects image data dynamically on the fly without *a priori* mapping or calibration.

Another advantage of the present invention is that it corrects image defects without reducing overall image resolution.

Another advantage of the present invention is that it corrects double line and double column defects.

Another advantage of the present invention is that it corrects image defects without creating additional defects.

Yet another advantage of the present invention resides in its combining image defect detection and correction into a single procedure.

Still another advantage of the present invention is that it leaves most image data unaltered.

Other benefits and advantages of the present invention will become apparent to those skilled in the art upon a reading and understanding of the preferred embodiments.

Brief Description of the Drawings

The invention may take form in various components and arrangements of components, and in various steps and arrangements of steps. The drawings are only for purposes of

illustrating preferred embodiments and are not to be construed as limiting the invention.

FIGURE 1 is a diagrammatic illustration of a Fluoro Assistant CT system (FACTs) attached to a CT scanner employing the adaptive median filter in accordance with the present invention; and,

FIGURE 2 is a flow chart illustrating details of the defect detection and correction procedure in accordance with the present invention.

Detailed Description of the Preferred Embodiments

With reference to FIGURE 1, a fluoroscopic system **10** radiographically examines and generates diagnostic images of a subject disposed on a patient support **12**. More specifically, a volume of interest of the subject on the support **12** is moved into an examination region **14**. An x-ray tube **16** mounted on a rotating gantry projects a beam of radiation through the examination region **14**. A collimator **18** collimates the beam of radiation in one dimension.

The two-dimensional x-ray detectors **20** includes a two-dimensional array of photodetectors connected or preferably integrated into an integrated circuit. A scintillator, comprising a thallium-doped CsI layer, is deposited directly on the photodetector array. X-rays that have traversed the examination region **14** are received through the front face of the scintillation crystal. The scintillation crystal converts these x-rays into a flash or scintillation of visible light of a characteristic wavelength. The visible light exits the scintillation layer via a surface that is optically coupled to the photodetectors. Light from the scintillation layer is converted by the photodetector into corresponding electrical signals indicative of the intensity of the received radiation which is indicative of the integrated x-ray absorption along the corresponding ray between the x-ray rube and the scintillation layer segment.

The electrical signals, along with information on the angular position of the rotating gantry, are digitized by analog-to-digital converters. The digital diagnostic data is processed for offset and gain calibration by an image calibration processor **30**. The digital image representation includes a rectangular array of digital pixel values, each indicating the gray scale of a corresponding image pixel. For simplicity of illustration, a two-dimensional array corresponding to a projection image is described in detail. However, it is to be appreciated that the present technique is also applicable to three-dimensional arrays representing a volume.

When the projection image representation is generated, lines of pixel values are passed through an adaptive filter **32**, preferably a median filter. The adaptive median filter **32** performs a real-time detection and correction of image defects. Such image defects may be due to pixel defects, line defects, double-line defects, column defects, and double-column defects in the two-dimensional detector panel **20**, as well as random defects. For an nxn adaptive filter, read out lines of pixel values are temporarily stored in n-1 digital line memory devices $\mathbf{34_1}$, $\mathbf{34_2}$,.... In the illustrated 3x3 embodiment, the buffer stores the two preceding lines. A field programmable gate array (FPGA) **40** reads the current and two preceding data lines. As the oldest data line is read out of one buffer, the current data line is read into it.

The FPGA **40** includes a comparitor circuit or processor **42** which compares the pixel values of the three lines with threshold criteria **44**. Various threshold criteria are contemplated. Preferably, each pixel value of the middle line is compared with the eight immediately surrounding pixel values in itself and in the two adjoining data lines. If a pixel value varies by 20% or another preselected percentage from the median value of its eight nearest neighbors, an adaptive filter processor **46** replaces it with the median value of its nearest neighbors. Rather than (or in addition to) the 20% threshold

criteria, each pixel value can be compared with other criteria including full black and full white. The adaptive filter replaces each pixel value that fails these criteria with a median or other preselected function of its nearest neighbors that are not full black or white. Pixel values which pass the test are not altered by the adaptive filter. In this manner, any (if any) pixel values of the middle data line that failed the test are replaced with median filtered values and are passed by the adaptive filter for further processing. After the middle data line is scanned with the nxn kernel, the lines of data are indexed with a new line added and the most remote line dropped.

The implementation of the adaptive median filter in a pipelined architecture yields one processed pixel output for every unprocessed input pixel, often referred to as a systolic processor. The outputs are delayed with respect to the input by the pipeline processing delay time. More specifically, after nxn pixels are latched by the FPGA, a sorting algorithm within the FPGA yields the median value of the nxn kernel. In parallel, the unprocessed value of the given pixel is stored and made available along with the median value. Also in parallel, a multiplier within the FPGA computes a threshold value for the pixel being examined by multiplying the unprocessed or original pixel value by the predefined defect threshold, 0.2 for example. The difference between the original unprocessed pixel value and the median value is determined by a sort and subtraction algorithm within the FPGA and then compared to the threshold value. If the difference value is greater than the threshold value, the median value is substituted for the original pixel value at the output of the FPGA. Otherwise, the original pixel value is at the output of the FPGA. Artisans will appreciate that all data, including original pixel, median value, threshold value, and difference value, are synchronized through pipelined latches. Further, the horizontal and vertical raster synchronization signal timing relationship with respect to a given pixel is also maintained using shift registers.

The filtered image is stored in a volumetric image memory **50**. A video processor **52** processes the defect-corrected image to create projection images, and reformats them for display on a monitor **54**, such as a video or LCD monitor.

With reference to FIGURE 2 and continuing reference to FIGURE 1, a more detailed method and software based apparatus for detecting and correcting digital image defects begins at step **100** with the inputting of lines of digital pixel values and a predefined defect threshold into the adaptive median filter. Again, the predefined defect threshold is used by the adaptive median filter to determine whether a given pixel of the image should be replaced by the median value of the neighboring pixels or should be left unaltered. The inputted line of pixel values is then copied **110** into a correction memory for processing. A kernel of nxn pixels is selected **120**, with the central pixel value of the kernel being the candidate pixel value to be examined. In one embodiment, a 3x3 kernel is selected with the center pixel of the kernel being examined and compared to the eight adjacent nearest neighbor pixels.

The selected nxn kernel is reordered **130**. More particularly, the pixel values of the selected nxn kernel are sorted numerically by value and adjacent pixels of like value are merged into a single pixel value. A median value of the reordered and condensed kernel is calculated **140**. For example, in a 3x3 kernel of nine pixels, the pixel value that is being processed is compared to the median value of the nine pixels in the kernel. However, before the median value of the kernel is calculated, any pixel values in the kernel of like value are combined or condensed into a single representation of the common value. For example, three adjacent pixels may each have a value of "1". These three pixels are then merged into a single merged pixel having a value of "1". Then, a median value of the six pixel values reordered kernel is calculated. The median is advantageous for its computational simplicity, speed and ability to correct double line and double column

defects. However, other functions of the surrounding pixel values based on spread, slope, weighted averages, more complex and other functions are also contemplated.

A threshold value for the particular pixel being examined is calculated **150**. The threshold value is calculated, in the preferred embodiment, by multiplying the candidate pixel value by the predetermined defect threshold criteria. In addition, a reference value is calculated **160** by subtracting the median value of the selected kernel from the candidate pixel value. The calculated difference value **160** is then compared **170** to the calculated threshold value **150**. If the difference value is greater than the threshold value, the original pixel value is replaced **180** by the median value of the kernel in which the candidate pixel is located **180**. If the difference value is less than the threshold value, the candidate pixel is determined to be free of defect and the original candidate pixel value remains unchanged.

In one embodiment, the defect threshold is selected to be 20%. In other words, candidate pixel values which differ by greater than 20% from the median value of the kernel in which they are located are replaced by the median value of the kernel. Conversely, candidate pixel values that are within 20% of the median value of the kernel in which they are located remain at their original unprocessed pixel value. In an alternate embodiment, the defect threshold may be chosen such that the adaptive median filter searches only for pixels having a zero value, i.e. dark, or a maximum value, i.e. white. It is to be appreciated that the following filtering procedure is performed on all of the pixel values for real-time detection and correction of image defects.

It is to be appreciated that the adaptive median filter is effective in correcting pixel defects, line and column defects, including double line and double column defects, bipolar line and column defects, such as one line white and adjacent line black, cluster pixel defects, ASIC boundary lines, driver line noises, noisy pixels, and the like.

Although median filters are particularly effective, it is contemplated that other filters and interpolation techniques can be utilized. For example, the pixel being examined and any zero level pixels and saturated pixels can be excluded from the kernel median. Pixel values in the kernel can be preferentially weighted. Other kernels, such as larger kernels, non-square kernels, and the like are also contemplated. Higher order interpolations may also be utilized.

Having thus described the preferred embodiments, the invention is now claimed to be:

1. A method for real-time detection and correction of digital image defects due to defective detector pixels, the method including:

(a) identifying a candidate pixel value in image data **(100)** which includes a plurality of candidate pixel values and corresponding kernels of neighboring pixel values;

(b) calculating **(140)** a reference value from the kernel of neighboring pixel values;

(c) comparing **(170)** a relationship between the candidate pixel value and the reference value with a threshold criterion; and

(d) based on the comparing step **(170)**, one of (1) replacing **(180)** the candidate pixel value with a function of the neighboring pixel values and (2) retaining the candidate pixel value.

2. The method according to claim 1, further including:

calculating **(140)** a median pixel value for the kernel;

calculating **(150)** a threshold value based on an unprocessed pixel value of the candidate pixel and a predefined defect threshold;

calculating **(160)** a difference value between the median pixel value and the unprocessed pixel value; and

comparing **(170)** the difference value **(160)** to the threshold value **(150)**.

3. The method according to claim 2 wherein:

the candidate pixel value is replaced **(180)** by the median pixel value for pixel locations in which the difference value **(160)** is greater than the threshold value **(150)**; and

the candidate pixel value is retained where the threshold value **(150)** is greater than the difference value **(160)**.

4. The method according to any one of claims 1, 2, and 3 wherein calculating **(140)** a median pixel value includes:

sorting **(130)** the pixel values of the selected kernel according to numeric value; and,

merging **(130)** like pixel values into a single value prior to calculating the median pixel value.

5. The method according to any one of claims 1-4, wherein each kernel is three pixels by three pixels, and the defect threshold is 20%.

6. An adaptive median filter **(32)** for detecting and correcting defects in a digital image representation due to defective detectors in a radiation detector array **(20)**, the adaptive median filter **(32)** comprising:

a memory **(34_1, 34_2)** which stores each candidate pixel value and neighboring pixel values;

a processor **(40)** which:

calculates **(42)** a reference value from the neighboring pixel values,

compares **(42)** a relationship between the candidate pixel value and the reference value with a threshold criterion **(44)**;

based on the comparison **(42)**, one of (1) replaces **(46)** the candidate pixel value with a function of the neighboring pixel values and (2) retains the candidate pixel value.

7. The adaptive median filter **(32)** according to claim 6, wherein the processor **(40)** calculates a median value of the pixel value in a kernel corresponding to the candidate pixel value, at least one of the reference value and the function of neighboring pixel values being the median value.

8. The adaptive median filter **(32)** according to claim 7, wherein the candidate pixel value is replaced with a corresponding median value if the candidate pixel deviates from the reference value by more than a preselected percentage.

9. The adaptive median filter **(32)** according to any one of claims 6-8, wherein the processor **(40)** includes a field programmable gate array.

10. The adaptive median filter **(32)** according to any one of claims 6-9, wherein the adaptive median filter **(32)** detects and corrects defects in digital image representations produced by:

a radiographic apparatus **(10)** having a penetrating radiation source **(16)** for projecting x-rays across an examination region **(14)**, a plurality of radiation detector arrays **(20)** disposed across the x-ray examination region **(14)** from the penetrating source **(16)**, the detector arrays **(20)** including analog to digital converters for converting analog signals into digital signals, and an image calibration processor **(30)** for calibrating and reconstructing the digital signals into pixel values of a digital image representation.

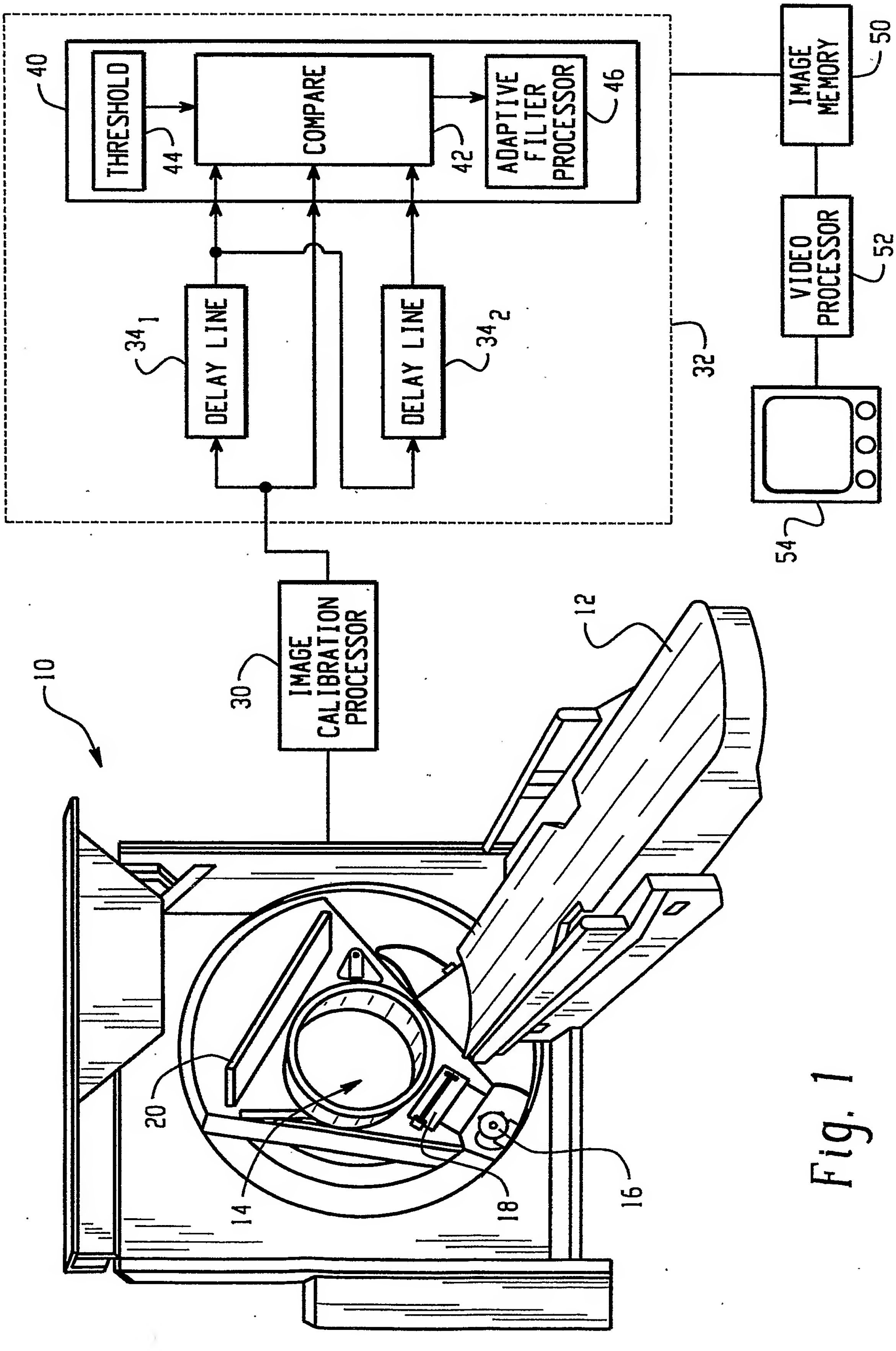
THRESHOLD
COMPARE
ADAPTIVE FILTER PROCESSOR
IMAGE MEMORY
VIDEO PROCESSOR
DELAY LINE
DELAY LINE
IMAGE CALIBRATION PROCESSOR
40
44
42
46
50
52
34_1
34_2
32
54
30
10
12
20
14
18
16

Fig. 1

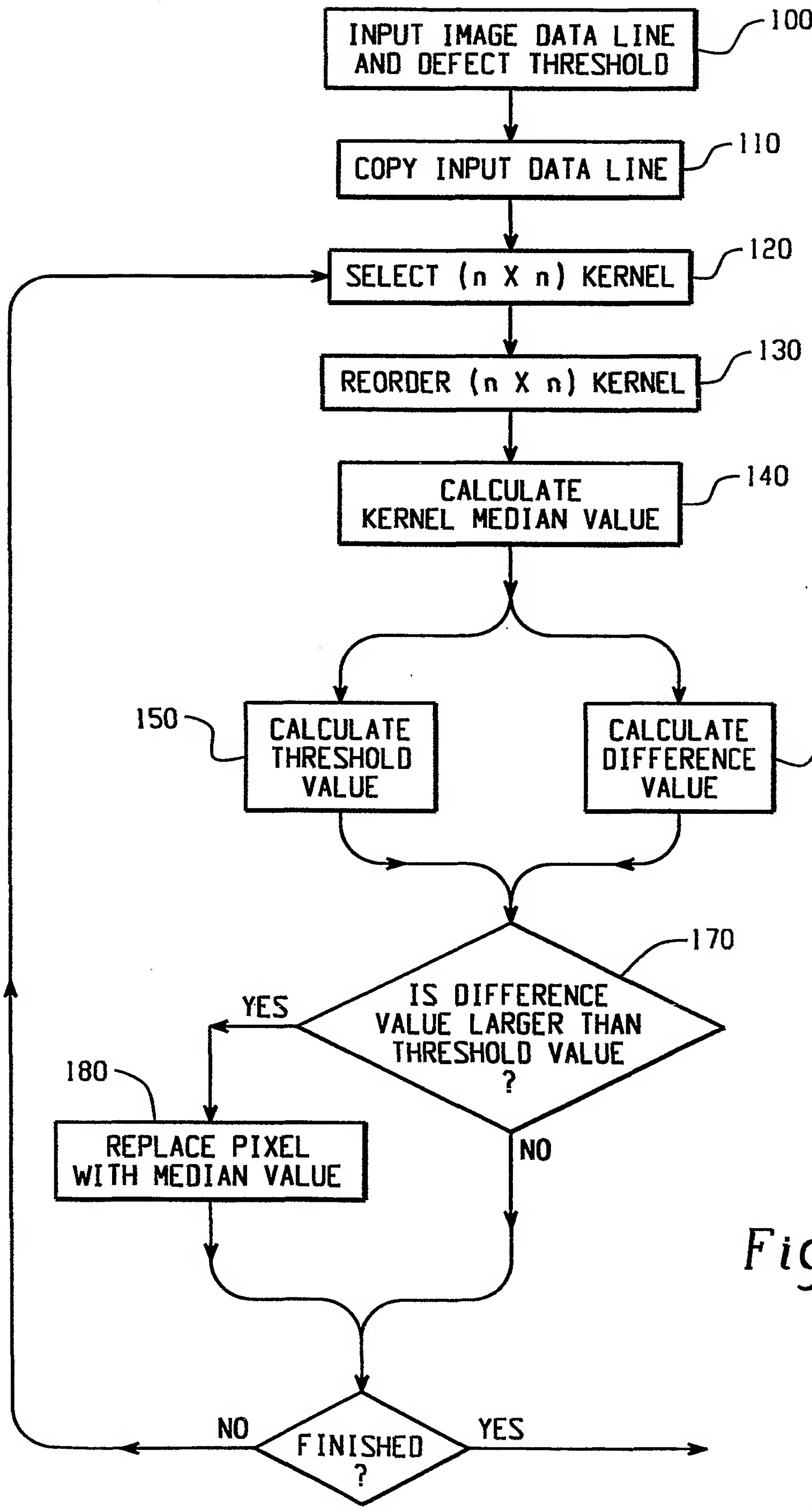
INPUT IMAGE DATA LINE AND DEFECT THRESHOLD
100
COPY INPUT DATA LINE
110
SELECT (n X n) KERNEL
120
REORDER (n X n) KERNEL
130
CALCULATE KERNEL MEDIAN VALUE
140
CALCULATE THRESHOLD VALUE
150
CALCULATE DIFFERENCE VALUE
160
IS DIFFERENCE VALUE LARGER THAN THRESHOLD VALUE ?
170
YES
NO
REPLACE PIXEL WITH MEDIAN VALUE
180
FINISHED ?
NO
YES

Fig. 2